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Using present and past climosequences to estimate soil organic carbon and related physical quality indicators under future climatic conditions

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ABSTRACT

This research aimed at testing the use of present and past climosequences to estimate soil organic carbon (SOC) and related physical quality indicators under future climatic conditions. The influence of climate on soil features was studied for four combinations of typical Mediterranean soil types and cropping systems, placed along climosequences of the past (P1: 1961–1990), present (P2: 1981–2010) and future (P3: 2021–2050). The four test areas were located in Italy, each one characterized by the same soil typology and cropping system, placed on similar morphological position and parent material, wide enough to cross climatic boundaries. Legacy soil profiles that were sampled in the P1 time-period were re-sampled in 2010–2011, to check for possible variations in soil characteristics. Besides SOC content and stock (C_{stock}), we examined some physical quality indicators for which the existence of relations with SOC is well-known, namely soil compaction and soil crusting susceptibility, soil erodibility, and soil loss by water erosion.

Among several climatic indexes, the de Martonne index (IDM) resulted the most correlated with SOC. The IDM vs. SOC relationship was significant and not different in both P1 and P2 climosequences, highlighting the temporal stability of the relation between climate and SOC content. In the Vertisols of Sicily, cultivated under cereals, the P3 climosequence predicted a SOC reduction of more than 11%. This will lead to an increase of soil erodibility, susceptibility to compaction, and surface crust formation. On the contrary, in the Luvisols under forage crops of the Po Plain, a substantial C_{stock} increase (28.8%) is expected, with a consequent improvement in soil physical indicators. For the Luvisols under meadows of Sardinia, an increase in erosion of 13.5% is expected, because of increased precipitation volume (7.4%) and aggressiveness. In the Andosols under olive trees of Campania there is a predicted reduction in the C_{stock} (−6.3%) and an associated increase in soil loss (4.6%), while no marked variation is expected for the other soil physical indicators.

We can conclude that climosequences are a useful tool to predict the future dynamics of some soil physical characteristics affected by climate change. C_{stock} and soil loss by water erosion are expected to change significantly under future climatic conditions, while minor changes are observed for erodibility, compaction and crusting susceptibility, even when SOC variations are significant. In the climosequences, the considered soil physical quality indicators resulted proportionally more affected by the cropping system than by the climate and, within the same cropping system, more variable according to the climate than the time. This outcome confirms the fundamental role of soil physics in controlling the resilience of the soil system to climate change.

1. Introduction

Agricultural production is dramatically affected by climate variability and change (Parry et al., 2004; Lal, 2004; Olesen et al., 2011; Lobell et al., 2011). Producers, land managers, and other decision makers need information about the effects of climate change on cropping systems, to develop mitigation and adaptation strategies, and policy measures (Smit et al., 2000; Olesen and Bindi, 2002). Due to the great variability of climate and soil cover, adaptation measures should be tailored according to specific conditions to be really effective (Thornton et al., 2009; Walthall et al., 2012).

Planning specific interventions and prescriptions should be based upon scientific findings and monitoring activities. However, estimates on the real impact of climate change on definite cropping systems have

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produced variable results, in function of the local climatic conditions, intensity and velocity of change, and adoption of different management options (Loarie et al., 2009; Lal et al., 2011). Some authors even consider a moderate climate change beneficial for specific cropping systems and environments, if adaptation options are implemented (Hatfield et al., 2011; Howden et al., 2007). Nevertheless, there is a common agreement that in many areas of the world crop yields might be depressed under the climatic conditions of next decades, if current management practices are not modified (Tubiello et al., 2000; Ciais et al., 2005).

Although land use and management changes are expected to play a greater role than climate change on soil properties and functions (Valentin et al., 2005; Huang et al., 2007; Lal et al., 2011; Fantappiè et al., 2011), projected climatic conditions seem to jeopardize several soil qualities and functions (Lal, 2004). Soil organic matter (SOM) and its components, including biological activity, are the most sensitive and dynamic properties, frequently used as crucial indicators for monitoring land degradation processes, as well as adaptation and restoration strategies (Kirschbaum, 1995; Harris, 2003; Fantappié et al., 2010; Costantini et al., 2016). The study of soil physical and hydrological variations related to climate change is much less investigated, in spite of their paramount importance in shaping soil services (Powlson et al., 2011).

Future changes of soil physical and hydrological characteristics have been estimated in Chinese and Mediterranean watersheds, where soil erodibility is deemed to show a significant increasing trend, especially in cultivated fields (Zhang and Liu, 2005; Nunes et al., 2008). Under most probable climate change scenarios, the hydrological characteristics of Calcic Chernozems of Hungary are estimated to deteriorate (Hernádi et al., 2009). In Scotland, soil workability is foreseen to worsen in the changed climate, because of an expected increase in winter rainfall (Cooper et al., 1997).

It is well known that the study of climate change impact on properties of agricultural soils can be pursued with several approaches

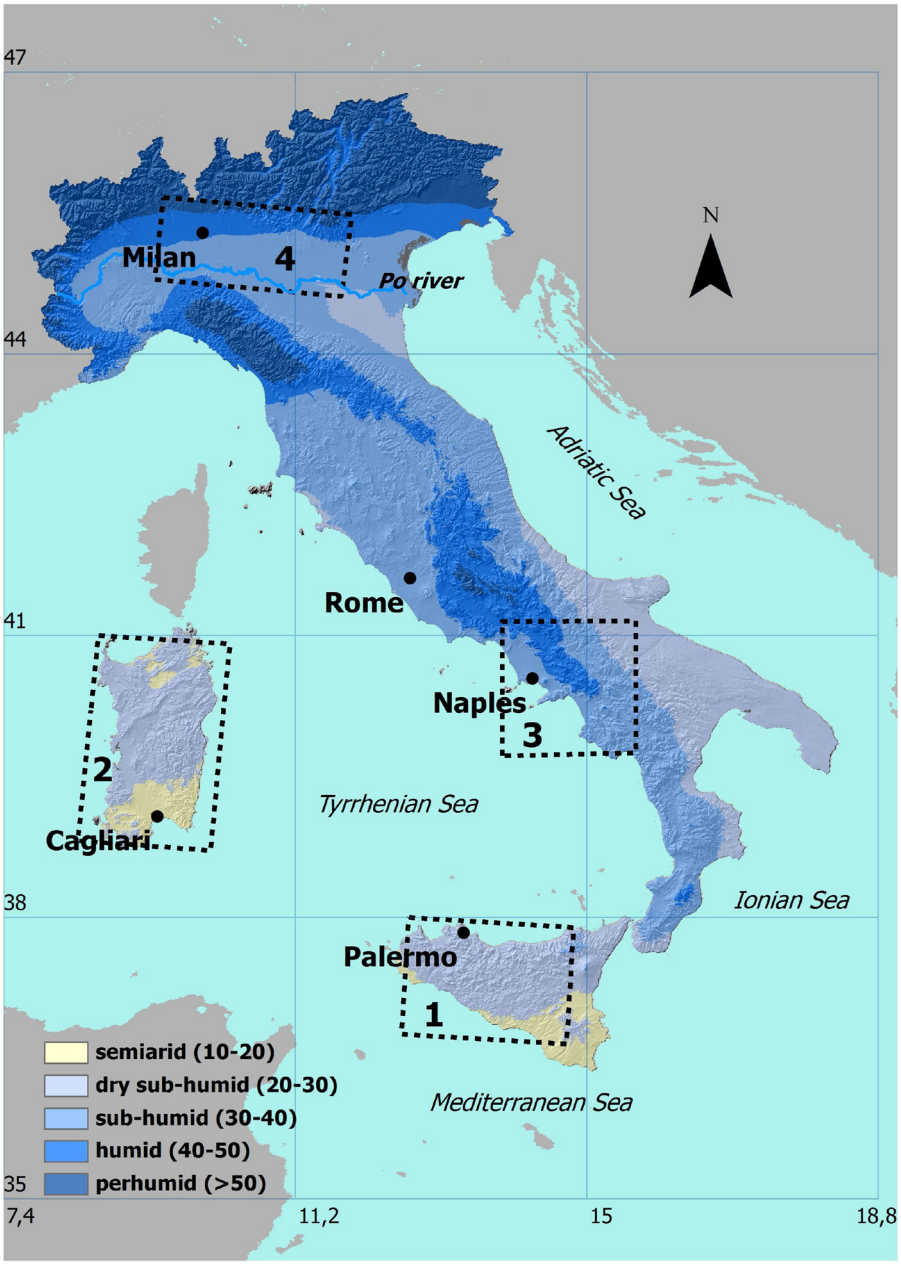

Fig. 1. Test areas and aridity classes (1981–2010) of Italy according to the de Martonne (1926) classification. The numbers from 1 to 4 identify, in the order, the test areas of Sicily, Sardinia, Campania and Po Valley.

(White et al., 2011). Different kinds of crop growth models have been developed to estimate crop and soil behaviour as driven by climatic conditions and management options (Rauff and Bello, 2015). According to the specific purposes and the scale of interest, models have been applied at global (Cramer et al., 2001), continental (Ludwig and Asseng, 2006), multi-national (Eitzinger et al., 2004), and national scale (Díaz and Cabido, 1997; Erda et al., 2005), while more detailed studies are rarer, because of the difficulties in downscaling the local features of future climates (Herrmann et al., 2011; Pizzigalli et al., 2012) and of the uncertainties of climate projections at the local scale into the 21st century (Forster et al., 2013).

The "space-for-time" substitution approach is widely used in biological sciences to infer future trajectories of ecological systems from contemporary spatial patterns (Blois et al., 2013). The approach has also been applied to the study of soil properties along climosequences and to estimate future soil changes at the national and regional scale (Burke et al., 1989; Tate, 1992; Garcia-Estringana et al., 2013; Bojko and Kabala, 2016). The rationale is that the comparison of similar soils, formed by the same set of pedogenetic factors, but under different climates, could allow an estimation of the changes that might occur over time.

This research aimed at testing the use of present and past climosequences to estimate variations in soil organic carbon (SOC) and related physical quality indicators under future climatic conditions.

2. Material and methods

2.1. Test areas and cropping systems

The Mediterranean region is considered particularly vulnerable to climate change (Giorgi and Lionello, 2008), because of the geographic setting and climatic features, and the high vulnerability of soils (Mitchell et al., 2005; Costantini and Lorenzetti, 2013). The test areas were located in Italy, from the 37th to the 46th parallel North, and were wide enough to cross climatic boundaries of the main Mediterranean climates, namely sub-oceanic, sub-continental, and subtropical (Finke et al., 1998; Costantini et al., 2013a), as well as the de Martonne aridity classes (de Martonne, 1926) (Fig. 1). For this study, four Mediterranean cropping systems and soil types were selected as representatives: i) cereals on clayey Vertisols, ii) permanent pastures and meadows on sandy loam Luvisols, iii) specialized olive tree groves on Andosols, and iv) livestock fodder on loamy Luvisols. The extension of each test area was the sum of single parcels having same soil type and cropping system.

The selected time series (30-year period) were: the 1961–1990, named period 1 (P1) and considered as the baseline climate by most authors (e.g., Hulme et al., 1999; IPCC, 2006; Christensen et al., 2007), the decade closest to the present (1981–2010), named period 2 (P2), and the future climate projection (2021–2050), considered as period 3 (P3). Periods 1 and 2 are not mutually exclusive since we considered it to be more effective to compare two 30-year periods (even with a decade overlapping) than a 30-year period with a 20-year one. This is particularly important for precipitation, that in Mediterranean region is affected by a strong interannual and interdecadal variability (Dunkeloh and Jacobeit, 2003; Mariani and Parisi, 2014).

2.1.1. Cereals on clayey Vertisols (CV)

The test area, of about 350,000 ha, is located in Sicily and extends along a NW-SE direction from the province of Trapani up to that of Ragusa (Fig. 2). The investigated soils, developed on Pliocene marine deposits, are characterized by clay and clay loam texture and are classified as Calcic Vertisols (IUSS, 2006) or as Typic Haplusterts, Typic Calcixererts, and Typic Calcitorrerts (Soil Survey Staff, 2010).

These lands are under winter cereals arable crops, mainly durum wheat (Triticum durum) and barley (Hordeum vulgare L.). The cropping system, widespread in Sicily since the Roman time, is traditionally based on monoculture, unevenly interrupted every about 5-years with a pulse such as sulla (Hedysarum coronarium L.), vetch (Vicia faba minor), clover (Trifolium repens), chickpea (Cicer arietinum) or bean (Phaseolus vulgaris L.) or by fallow.

2.1.2. Permanent pasture and meadows on sandy loam Luvisols (PL)

The test area is located in Sardinia and covers about 170,000 ha in a SE-NW direction (Fig. 2). Starting from the South coast (Cagliari), the investigated soils extend up to Oristano and the northern coast of the island. These soils developed on Pleistocene alluvial deposits and are classified as Chromic Luvisols (IUSS, 2006) or as Typic and Ultic Haploxeralf (Soil Survey Staff, 2010). They exhibit low fertility, low in nutrients and soil organic carbon (SOC) content, sandy loam texture, and are quite shallow, skeletal, and rather compact. Grasses and legumes, such as fescue (Festuca arundinacea), ryegrass (Lolium perenne), oat (Avena sativa L.), bromes, clover (Trifolium subterraneum L.) and alfalfa (Medicago sativa L.), mainly characterize the meadows. The PL cropping system can be considered representative of rangelands and extensive agricultural lands of the Mediterranean.

2.1.3. Olive tree cultivation on loamy Andosols (OA)

Olive (Olea europaea L.) tree groves, which occupy a surface of about 19,000 ha in Campania including the coastal strip and up to the Apennines foothills, cover this test area (Fig. 2). The soils evolved on debris foothills composed of limestone overlaid by pyroclastic deposits; they are classified as Vitric Andosols (IUSS, 2006) or as Typic and Alfic Haplustands (Soil Survey Staff, 2010), and have moderately expressed andic characteristics. They are particularly fertile loamy soils, which support high value and intensive agro-ecosystems, among the most productive of Italy (Di Gennaro et al., 1995). However, due to their chemical and physical characteristics, such as poor adhesion to substrates, low internal cohesion (Maeda et al., 1977), high susceptibility to liquefaction (Soil Survey Staff, 2004), high hydraulic conductivity, and water retention (Terribile et al., 2000), these soils show a considerable environmental sensitivity and fragility. In particular, heavy rainfall could create favourable conditions for the triggering of landslides, mudflows, and severe soil erosion.

2.1.4. Forage and livestock production on loamy Luvisols (FL)

The test area is located in the Po Plain and covers about 150,000 ha in the high plain of the Lombardy and Veneto regions (Fig. 2). They are representative of the most intensively cultivated agricultural lands of Italy. The main crops are silage corn (Zea mays L.) and alfalfa, cultivated in rotation for livestock fodder. The investigated soils are Alfisols developed on Pleistocene fluvial and fluvioglacial deposits, with a homogeneous loamy texture and good drainage. They belong to Chromic Luvisols (IUSS, 2006) or to Typic Haplustalf and Hapludalf (Soil Survey Staff, 2010). They are prime farmlands, where farmers obtain high crop yields through intensive agricultural management.

2.2. Selection of the sampling sites

In each test area, the sites to be re-sampled were selected from the Italian soil database (Costantini et al., 2013b). Soil profiles located along a climatic gradient, belonging to the same soil typology, placed on similar morphological position and parent material, and under the same cropping system, were selected. As a whole, 59 legacy soil profiles, which had been described, sampled and analysed in the P1 time-period, were selected. The same profiles were re-sampled in the years 2010–2011 to check for changes that may have occurred in soil characteristics. In the same years, to improve the spatial representativeness of the soil-climate relationships, we sampled further 55 soil profiles. Table 1 shows the number of soil profiles described and analysed in the different cropping systems and time-periods.

During the 2010–2011 soil survey, samples throughout the 0–30 cm depth layer were taken by hand auger drillings, and analysed. The

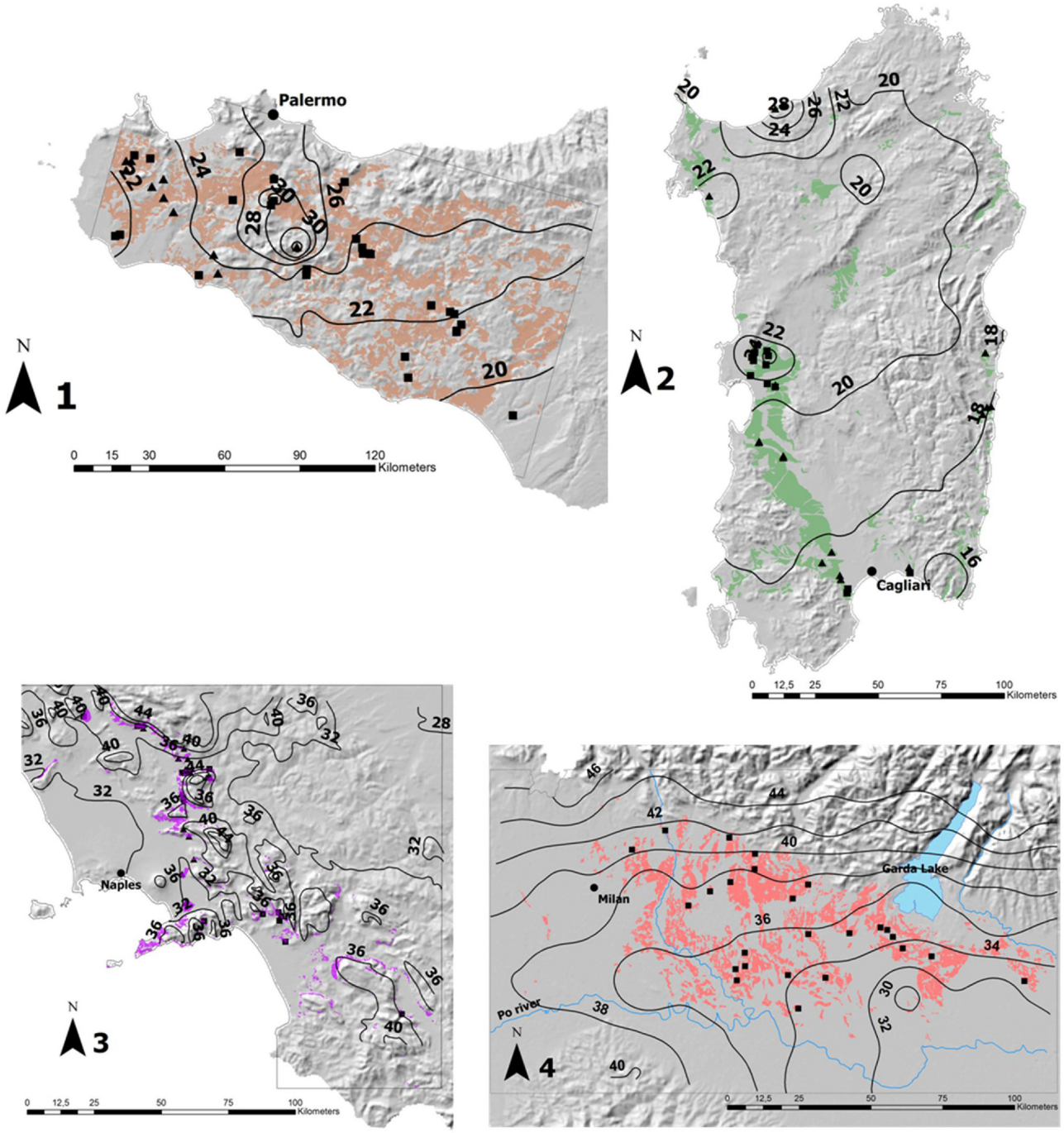

Fig. 2. Spatial distribution of cropping systems and soil profiles location. Black squares refer to soil profiles sampled both in the P1 and P2 time-periods, black triangles refer to profiles sampled only in P1. Iso-IDM lines of the P2 time-period are over imposed. The numbers from 1 to 4 identify, in the order, the test areas of Sicily, Sardinia, Campania and Po Valley.

thickness of 0–30 cm was chosen as it was within the plough layer of all cultivated crops, as reported in the legacy soil profile description. The auger holes were positioned in correspondence of the legacy profile position. Moreover, within a neighbourhood of about 200 m from the position of each legacy profile, additional 4 bulk soil samples were taken (0–30 cm depth) to account for local variability. In proximity of each drilling point, surface (0–30 cm) undisturbed soil samples were also collected by core method to determine bulk density.

The permanence of the same cropping system over time-periods P1 and P2 in each sampling site (old and new) was checked through a multi-temporal remote analysis. The analysis was performed by using orthophoto, both in digital and paper format, and Landsat MSS satellite images (60-m pixel size) taken every 18–16 days during the 1970–2010 period (Bocci et al., 2014). MODIS images of the decade 2001–2010 were utilized to provide a check of the land use of the sites with information at high resolution time (16 days) and moderate spatial resolution (250 m). The products of the MOD13Q1 series (Vegetation Indices 16-Day L3 Global 250 m) were used, extracting the value of NDVI for each site and date. The images were processed and filtered using the "ModisTools" and "Signal" packages of the R 3.x software (Kim et al., 2014). Subsequently, a specific script in Python language in ArcGis environment allowed to extract the respective NDVI value for each site and date. The analysis of the time series of the NDVI vegetation index allowed us to reconstruct multi-temporal signatures that

Table 1
Number of soil profiles sampled in the different cropping systems and time-periods. CV: Cereals on clayey Vertisols; PL: Permanent pasture and meadows on sandy loam Luvisols; OA: Olive tree cultivation on loamy Andosols; FL: Forage and livestock production on loamy Luvisols. P1: 1961–1990; P2: 1981–2010.

Cropping systems	Legacy profiles sampled both in P1 and P2	Further profiles sampled in P2 only	Total
CV	18	16	34
PL	10	18	28
OA	7	21	28
FL	24	0	24
	59	55	114

describe with high chronological detail the trend of this parameter, directly correlated to phenological phases and crop types (Verbesselt et al., 2010), thus allowing an objective evaluation of the dynamics of land use in the test areas of the project.

A database was built to collect all relevant information related to each soil climosequence, including i) quantitative data concerning soil properties deemed to be sensitive to climate change (i.e., pH, electrical conductivity, organic C content, total N, bulk density, water retention capacity), ii) site characteristics (latitude, longitude, altitude, aspect and slope), iii) basic climatic data (mean rainfall and temperatures on a monthly and annual basis) for each decade (P1, P2 and model generated P3 time-period).

2.3. Chemical and physical soil analyses

Chemical and physical characterization of the soil was made according to internationally recognized analytical methods: pH, electrical conductivity (EC 1:2.5), total limestone ($CaCO_3$) (Sparks, 1996), bulk density (BD) by the core method (Blake and Hartge, 1986) and plant available water capacity (AWC) by pressure plate extractors (Klute, 1986). Soil organic carbon and total nitrogen (N) content were measured by dry combustion on a Thermo Flash 2000 CN soil analyser. To this aim, 20–40 mg of soil were weighed into Ag-foil capsules and pretreated with 10% HCl until complete removal of carbonates. Soil particle size distribution was determined by the Sedigraph X-ray attenuation method (Andrenelli et al., 2013).

The legacy values of SOC had been obtained by the Springer and Klee (1954) and Walkley and Black (1934) methods, corrected to make them comparable with CN soil analyser. The main test area characteristics and soil chemical and physical properties are reported in Table 2.

2.4. Soil physical quality indicators and organic carbon

Soil quality indicators are measures of soil functional state (Arshad and Martin, 2002). Soil organic matter is long since the most largely used quality indicator (Reeves, 1997). The role that organic carbon plays on physical, chemical and biological soil properties is well known (Stevenson, 1994; Wander, 2004). With regard to the physical aspects, SOC promotes the structuring processes, the stability of the aggregates and the infiltration of water, reducing the surface water runoff and, consequently, the erosion risk (Lal et al., 1998). Organic carbon expands the range of soil workability, since it increases the threshold moisture content at which soil assumes plastic behaviour. SOC also induces a greater resistance to compression, effectively hindering soil compaction (Soane, 1990) and surface crust formation (Sumner and Stewart, 1992).

Major soil physical quality indicators that are affected by organic carbon were examined, namely soil compaction and crusting susceptibility, soil erodibility, and soil erosion by water. Bulk density was excluded, since no significant relationship with organic carbon content was identified, probably because of the low values of SOC of the studied soils.

The equations used for estimating soil organic carbon stock (C_{stock}) and physical quality indicators are reported below, together with a brief description.

2.4.1. Soil organic carbon stock (C_{stock})

The C_{stock} of the surface layer (0–30 cm), expressed in kg m^{-2}, was calculated by the following equation (IPCC, 2003):

$$C_{stock} = SOC*BD*H*\frac{(100 - SK)}{100}$$

Where SOC is the soil organic carbon content (% by weight); BD is the bulk density (g cm^{-3}); H is the layer depth (3 dm); SK is the skeleton content (% by weight).

2.4.2. Soil compaction susceptibility

Soil compaction can be defined as a process of densification in which porosity is reduced, inducing significant changes of structural properties and soil behavior, as well as of its temperature and moisture regimes (Soane and van Ouwerkerk, 1994). The susceptibility of the soil to compaction depends on its compressibility, defined as the ease with which the soil undergoes a decrease in volume when subjected to a mechanical load (pressure) (Stone and Larson, 1980).

Several studies have been conducted to evaluate the compressibility of unsaturated soils by calculation of the compression index (CI) (Larson et al., 1980; Gupta and Larson, 1982; Horn, 1988; Horn and Lebert, 1994; Smith et al., 1997a,b; Imhoff et al., 2004). Among them, the ones carried out by Smith et al. (1997a,b) by means of lab uniaxial compaction tests, produced equations with adequate predictive capability.

Below is reported the equation of Smith et al. (1997a):

$$CI = -0.09266 + 0.01576*(Si + Cl) - 0.00012*(Si + Cl)^2$$

where Si is % silt (2–50 μm) and Cl is % clay (< 2 μm).

The uniaxial compaction tests, however, may provide ambiguous information. Faced with similar CI values, the resulting bulk density values may be appreciably different (Smith et al., 1997b).

In order to obtain more reliable information on the actual compaction risk, the CI has been modified by introducing an additive factor, the bulk density at the reference pressure of 100 kPa ($\rho 100_{kPa}$). Similar to other authors (e.g., Dexter, 2004; Angers and Simard, 1986; Soane, 1990), Vignozzi et al. (2007) showed that soil compressibility is affected by even modest SOC content variations, and that $\rho 100_{kPa}$ is significantly related to SOC ($R^2 = 0.77$) according to the following exponential relationship:

$$\rho 100_{kPa} = 1.04231 + \exp(-0.486474 - 0.464448186*SOC)$$

Vignozzi et al. (2007) have therefore developed a new index of compaction susceptibility (CI_{new}) integrating the algorithm of Smith et al. (1997a) with the equation for estimating the $\rho 100_{kPa}$:

$$CI_{new} = -0.09266 + 0.01576 * (Si + Cl) - 0.00012 * (Si + Cl)^2 + \rho 100_{kPa}$$

2.4.3. Soil crusting susceptibility

Surface sealing and crusting are among the most common physical degradation phenomena of agricultural soils, and consist in the mechanical destruction of surface aggregates by raindrops impact and the following drying process (McIntyre, 1958; Chen et al., 1980; Valentin and Bresson, 1997). If the structural elements exhibit poor stability, they can easily be broken and release elementary particles and small aggregates, which cause the occlusion of the pores and the consequent reduction of water intake (infiltration rate) when mobilized (Sumner and Stewart, 1992).

Soil crusting susceptibility was evaluated by the FAO (1979)

Table 2
Mean values and standard error (in parenthesis) related to test area characteristics, and soil chemical and physical properties. CV: Cereals on clayey Vertisols; PL: Permanent pasture and meadows on sandy loam Luvisols; OA: Olive tree cultivation on loamy Andosols; FL: Forage and livestock production on loamy Luvisols.

		Cropping system and soil type			
Variable	Unit	Cereal on clayey Vertisols (CV)	Permanent pasture and meadows on sandy loam Luvisols (PL)	Olive tree cultivation on loamy Andosols (OA)	Forage and livestock production on loamy Luvisols (FL)
Latitude N	decimal °	37.6 (0.04)	39.8 (0.09)	41.1 (0.05)	45.4 (0.03)
Longitude E	decimal °	13.5 (0.09)	8.9 (0.07)	14.5 (0.05)	10.1 (0.08)
Elevation	m a.s.l.	361.2 (40.3)	22.6 (2.9)	264.7 (28.2)	99.9 (11.0)
Slope	(%)	8.3 (0.81)	3.9 (0.70)	13.5 (1.51)	3.8 (0.51)
Clay	g dag^{-1}	40.7 (1.4)	17.0 (1.8)	22.6 (2.3)	20.1 (1.1)
Sand	g dag^{-1}	24.3 (1.6)	53.8 (2.9)	42.0 (3.2)	40.9 (1.9)
pH H_2O (1:2.5)	(-)	7.5 (0.1)	6.5 (0.2)	7.7 (0.1)	7.2 (0.3)
E.C. (1:2.5)	mS cm^{-1}	0.39 (0.4)	0.14 (0.01)	0.25 (0.01)	0.22 (0.03)
SOC	(%)	1.21 (0.05)	1.04 (0.06)	2.23 (0.11)	0.81 (0.04)
N	(%)	0.13 (0.01)	0.07 (0.01)	0.23 (0.01)	0.16 (0.01)
$CaCO_3$	g kg^{-1}	146.7 (15.5)	16.0 (7.8)	100.4 (31.6)	18.5 (8.7)
FC	% vol	40.4 (1.3)	25.9 (1.6)	33.4 (1.4)	29.3 (1.2)
WP	% vol	22.2 (0.8)	11.5 (1.1)	18.0 (1.0)	13.4 (0.6)
AWC	% vol	18.2 (0.5)	14.4 (0.7)	15.4 (0.7)	15.9 (0.9)
BD	g cm^{-3}	1.15 (0.03)	1.43 (0.02)	1.03 (0.02)	1.28 (0.01)
Skeleton	% weight	2.8 (0.39)	23.3 (2.24)	24.6 (3.02)	8.2 (0.66)

crusting index (I_c, dimensionless), calculated according to the following equation:

$$I_c = \frac{1.5*(Si_f) + 0.75*(Si_c)}{Cl + 5.8*SOC}$$

where Si_f = % fine silt (2–20 μm), Si_c = % coarse silt (20–50 μm), Cl = % clay (< 2 μm) and SOC = % soil organic carbon, all expressed on a dry weight basis.

2.4.4. Soil erodibility

According to Wischmeier and Smith (1978), soil erodibility is defined as the rate of soil loss per erosivity index unit as measured on a standard plot 22.1 m long, having a 9% slope and under continuous clean-tilled fallow condition, with tillage performed up and downslope, and is one of the factors employed in the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) to evaluate the mean annual soil loss rate. Torri et al. (1997) formulated an equation to estimate the soil erodibility factor (K) of the USLE, expressed as (Mg/ha) [(MJ/ha) (mm/h)]$^{-1}$. It was based on a global dataset of 239 soils with skeleton amount of less than 10%; this equation requires information about the percent SOM content, in addition to data on particle size distribution of the fine earth fraction (< 2 mm):

$$K = 0.0293(0.65 - Dg + 0.24Dg^2) \times \exp\left\{-0.00037\left(\frac{SOM}{Cl}\right)^2 - 4.02Cl + 1.72Cl^2\right\}$$

where Cl is the soil clay content expressed as a fraction, and Dg is the Naperian logarithm of the geometric mean particle size distribution calculated according to Shirazi et al. (1988):

$$Dg = \sum_i f_i \ln(\sqrt{d_i}\, d_{i-1})$$

where d_i (mm) is the maximum diameter of the i_{th} class, d_{i-1} (mm) is the minimum diameter and f_i is the mass fraction in the corresponding particle size class. Since this equation needs information about SOM content, according to Nelson and Sommers (1996) we used the 1.724 conversion factor to convert the SOC into the corresponding SOM values.

2.4.5. Estimation of soil erosion rate

The implementation of the analytical data with information related to land use, together with the morphometric and climatic features of the area, made it possible to estimate the soil erosion rate for each test area by the Revised USLE (RUSLE) model (Renard et al., 1997). The model is based on the equation E = R × K × L × S × C × P linking soil losses (E, tons ha^{-1} year^{-1}) to rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover and management (C) and conservation practices (P). In particular, erosivity factor (R) has been estimated using the exponential equation of Ferrari et al. (2005), erodibility was determined by applying the formula of Torri et al. (1997), while the cover-management factor (C) was estimated as indicated in Bazzoffi (2007). With regard to the topographical (slope length) factor (LS), it was employed the algorithm of Mitasova et al. (2001). Since the RUSLE is applicable for areas that are non-affected by deposition processes or drainage network differentiation, this empirical model was used for slope lengths of less than 300 m. In this work, according to the suggestions of Engel (2003) and Gregori et al. (2006), a maximum slope length of 150 m was set up. The support practices factor (P factor) was not considered since it is difficult to estimate for large areas the combined effect of multiple conservation practices acted at local scale (Panagos et al., 2015).

2.5. Climatic processing

The monthly precipitation and temperature were calculated from the national climatic data (http://climagri.entecra.it/), for the nodes of a regular grid with a resolution of 30 km for each year of the 1961–2010 period. For each grid node falling in the four test areas (56 in Sicily, 50 in Campania, 57 in Sardinia, and 86 in the Po Plain), the average monthly rainfall and temperature values for P1 and P2 were calculated, by which it was possible to draw some climatic indexes with different degree of complexity. In particular, the following annual climatic variables and indexes have been elaborated: mean annual precipitation (MAP), mean annual temperature (MAT), de Martonne (1926) aridity index (IDM), FAO-UNEP (1977) aridity index (AI), 50-cm-depth mean soil temperature (MST, Costantini et al., 2001) and soil aridity index (SAI, Costantini and L'Abate, 2009).

Below are the formulas used to calculate the mentioned climatic indexes:

- IDM = MAP/(MAT + 10)
- FAO-UNEP AI = MAP/ETo Penman-Monteith
- MST = MAT + ((FC × 100) − 20.7)/7.9, where FC is the

Table 3
Correlation coefficient (r) and significance level (p-value) of the relationships between SOC content of P2 (1981–2010) of all sites of each cropping system, and climatic variables and indexes. IDM values are shown in bold since this index resulted, on average, the most significantly correlated. MAP: mean annual precipitation; MAT: mean annual temperature; IDM: de Martonne aridity index; AI: FAO-UNEP aridity index; MST: 50-cm-depth mean soil temperature; SAI: soil aridity index.

Study area	MAP		MAT		IDM		AI		MST		SAI	
	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value	r	p-value
Sicily	0.47	$2*10^{-8}$	−0.37	$1*10^{-5}$	**0.46**	**$3*10^{-8}$**	0.42	$4*10^{-7}$	−0.13	0.11	−0.37	$1*10^{-5}$
Sardinia	0.31	0.002	−0.10	0.30	**0.28**	**0.005**	0.30	0.003	0.20	0.06	−0.21	0.03
Campania	0.26	0.01	−0.30	0.004	**0.40**	**$2*10^{-4}$**	0.30	0.004	−0.29	0.007	−0.24	0.02
Po Plain	0.42	$2*10^{-6}$	−0.34	$1*10^{-4}$	**0.40**	**$5*10^{-6}$**	0.38	$1*10^{-5}$	−0.25	0.004	−0.21	0.02

volumetric water content at 50-cm-depth in decimal format

- SAI (dry days/year) = 44.53 + (MAT × 7.31) − (MAP × 0.06) − (AWC_50 × 0.23), where AWC_50 is the volumetric available water content (mm) of the 50-cm-depth soil moisture control section (Costantini et al., 2013a).

The considered climatic indexes were tested against the SOC content of P2 of all sites of each cropping system, to detect the most significant relationship (Table 3). Since IDM provided the most significantly correlated variable, it was selected as the reference climatic index for all the successive elaborations.

In addition, two indexes were used to characterize rainfall erosivity, according to Giordano (2009). We calculated, on a monthly basis: i) the Fournier climate aggressiveness index (MFI) modified by Arnoldus (1977), which takes into account rainfall variability and ii) the Bagnouls and Gaussen (1953) aridity Index (BGI), through which drought related phenomena are indicated by positive BGI values. Under Mediterranean climate, dryness promotes erosion processes, reducing the degree of vegetation cover and making the soil surface more vulnerable to erosion.

Below the formulas used to calculate these indexes are reported:

$$MFI = \sum_{i=1}^{12} \frac{P_i^2}{P_m}$$

Where P_i: average precipitation of the i^{th} month; P_m: mean (m) total annual precipitation, and

$$BGI = \sum_{i=1}^{12} (2T_i - P_i)*K_i$$

Where T_i: mean temperature of the i^{th} month; P_i: average precipitation of the i^{th} month; $K_i = 0$ if in the i^{th} month $2T_i - P_i \leq 0$, or $K_i = 1$ if in the i^{th} month $2T_i - P_i > 0$.

With regard to P3, we used the cumulative precipitation and average monthly temperatures produced by ARPA-SIMC (Regional Agency for Environmental Protection, Climate, Weather and Hydrological Service) of Emilia-Romagna for 4 grid nodes, one for each test area (Tomozeiu et al., 2010). Specifically, the following reference nodes were used: Francofonte for Sicily, Marrubiu for Sardinia, S. Salvatore Telesino for Campania and Carpaneto Piacentino for the Po Plain (Table 4).

ARPA-SIMC produced an Ensemble Mean (EM) of six Global Circulation Models (GCMs), according with the A1B scenario (Sheffield and Wood, 2008). The A1 scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Technological change in A1B scenario, in particular, is based on all energy sources, fossil and non-fossil. Each downscaled model output was made of seasonal levels of weather variables expected for the period 2021–2050, from which a weather generator was used to produce 50 projections of 365-days sequence (Tomozeiu et al., 2010).

Table 4
Geographical features of the 4 grid nodes used for the 2021–2050 climate projections.

Grid node	Lat.	Long.	Municipality	Test area
1019	37.246	14.887	Francofonte	Sicily
1118	39.803	8.648	Marrubiu	Sardinia
1221	41.224	14.497	S. Salvatore Telesino	Campania
1410	44.917	9.818	Carpaneto Piacentino	Po Plain

For each grid node, the average climatic scenario was calculated based on the 50 available simulations, and the above mentioned climatic indexes computed. For each climatic variable, the relative percentage variation was computed by comparing the P2 data with the corresponding of P3. To determine the future climatic indexes for the other grid nodes falling within the specific test area, the same percentage variation observed on the respective reference node was assigned.

The estimated value of the IDM for the 30-year period 2021–2050 was used to calculate the expected SOC content for the future scenario, by applying the different regression equations separately elaborated for each test area in P2.

Finally, to overlay climatic data to the shape of crop systems, we spatialized climatic variables from the regular grid at 30 km to a pixel of 500 m by a GIS, using the inverse distance method (IDW). We opted for the IDW method, instead of using geostatistical techniques, since a geostatistical approach (kriging/co-kriging) that used environmental covariates (elevation, latitude, distance to the sea) was already adopted to attribute climatic values to the grid nodes. According to Williams et al. (2001), in such case the further use of geostatistic is not correct and not needed, while IDW is a more proper way to spatialize data. The results obtained with IDW actually reflects the interaction with morphology, which was the most important covariate originally used (Fig. 2).

3. Results

3.1. Climate variations in the three time periods

3.1.1. Climatic variations at the reference grid nodes

Climatic characteristics of the 4 reference grid nodes are depicted in Table 5, referring to the 1961–1990 30-years baseline period, to the 1981–2010 and to the future scenario (2021–2050). For each climatic variable (v), the percentage variations (e.g., (v2-v1)/v1*100) between time periods P1, P2 and P3 are also reported.

The data displayed in Table 5 show higher mean annual temperature in P2 respect to P1, and also in P3 compared to current climate (P2) in all the grid nodes, with a maximum in Campania, where an increase of more than 1 °C is foreseen.

With regard to rainfall, trends are more articulated and uneven, in terms of both sign and magnitude. In Sicily, in particular, a small increase (2.8%) was registered from P1 to P2, while a rainfall reduction is expected in P3 (−12.2%); conversely, a decrease was observed in the Po Plain from past to more recent conditions (−7.0%), but a remarkable increase is foreseen for the future (14.1%). Even higher percentages of rainfall reduction in P2 with respect to P1 were recorded in Campania (−16.6%) and Sardinia (−11.7%), but the future climatic

Table 5
Mean annual values of total precipitation (P), air temperature (T) and climatic indexes (aridity index IDM, Fournier climate aggressiveness index MFI, Bagnouls-Gaussen aridity Index BGI) at the reference node of the grid during the three compared time periods. Percentage variations between the time periods are also reported.

Period	Grid node - Test area	P (mm)	T (°C)	IDM	MFI	BGI
P1	1019 - Sicily	520.6	16.6	19.6	83.9	170.9
(1961–1990)	1118 - Sardinia	596.7	16.5	22.6	86.3	145.1
	1221 - Campania	1070.4	13.7	45.2	133.8	42.6
	1410 - Po Plain	889.3	12.3	39.9	101.8	30.5
P2	1019 - Sicily	535.3	17.1	19.8	82.1	169.8
(1981–2010)	1118 - Sardinia	526.6	16.9	19.6	72.4	153.0
	1221 - Campania	892.8	14.2	36.9	107.5	57.6
	1410 - Po Plain	827.4	12.9	36.2	98.5	35.3
P3	1019 - Sicily	469.9	17.9	16.8	69.0	190.8
(2021–2050)	1118 - Sardinia	565.7	17.7	20.4	77.0	158.4
	1221 - Campania	912.6	15.3	36.1	97.7	37.7
	1410 - Po Plain	944.4	13.6	40.0	105.3	28.3
P2 vs. P1	1019 - Sicily	2.8	3.0	1.0	−2.1	−0.6
(% variation)	1118 - Sardinia	−11.7	2.4	−13.3	−16.1	5.4
	1221 - Campania	−16.6	3.6	−18.4	−19.7	35.2
	1410 - Po Plain	−7.0	4.9	−9.3	−3.2	15.7
P3 vs. P2	1019 - Sicily	−12.2	4.7	−15.2	−16.0	12.4
(% variation)	1118 - Sardinia	7.4	4.7	4.1	6.4	3.5
	1221 - Campania	2.2	7.7	−2.2	−9.1	−34.5
	1410 - Po Plain	14.1	5.4	10.5	6.9	−19.8
P3 vs. P1	1019 - Sicily	−9.7	7.8	−14.3	−17.8	11.6
(% variation)	1118 - Sardinia	−5.2	7.3	−9.7	−10.8	9.2
	1221 - Campania	−14.7	11.7	−20.1	−27.0	−11.5
	1410 - Po Plain	6.2	10.6	0.3	3.4	−7.2

scenarios show an increase in precipitation (2.2 and 7.4%, respectively). The annual rainfall variations are reflected in IDM values.

More detailed evaluations are possible through the analysis of the indexes obtained from monthly climatic data. It is noticeable that in Campania there is a progressive reduction in the values of rainfall concentration (MFI), which presumes a greater homogeneity in precipitation distribution during the year, including summer time. The remarkable future reduction of BGI values in Campania, where it is assumed a shift from dry to moist climatic conditions, is therefore attributable to a higher rainfall uniformity. In Sicily, by contrast, the cause of the marked BGI increase in P3, which reports an exacerbation of the already very dry climatic conditions, is attributable to the reduction of the rainfall. In the Po Plain, we expect a trend similar to that of Campania, that is, a large decrease of the BGI aridity index due to the combined effect of lower rainfall concentration and a noteworthy increase of total precipitation volumes. In Sardinia we observe a constant increase in the values of the BGI index, pointing to a progressive aridification of the climate, which extends in the future despite the slight increase of precipitation, because of the parallel concentration of rainfalls.

3.1.2. Climatic variations within the four cropping systems areas

Observing the IDM values displayed in Table 6, it can be noticed that there are important changes during the three studied time periods in the four cropping systems. The aridity index in CV improved of 1.3 IDM units passing from P1 to P2, but is deemed to worsen by 3.4 units in P3, moving from dry sub-humid to semi-arid. An opposite trend was recorded in the area under FL, which saw a climate class changing from humid to sub-humid (−5.4 IDM units), followed by an expected return to humid conditions in P3. The PL cropping system resulted instead relatively more stable in the passage between past, recent and future climate. On the other hand, OA reveals a progressive reduction of IDM values for the same time periods. This test area showed the highest variation in IDM and precipitation values between P1 and P2, with a reduction of 6.6 IDM units and 150 mm of rainfall, respectively (Table 6), determining the shift from humid to sub-humid IDM class.

Overall, the BGI values remained rather stable passing from P1 to P2. An important change is expected in P3 for OA, when it should switch from dry (50–130) to moist (0–50) class, while CV and PL should remain in the very dry (> 130) and FL in the moist class.

With regard to rainfall concentration, the areas in which the MFI index showed the greatest variations between the P1 and the P2 time periods are Campania and Po Plain, where a reduction of 21.2 and 7.7 units, respectively, was recorded; this corresponded to the transition from the high (120–160 MFI units) to the moderate (90–120) class of rainfall concentration in the OA cropping system area of Campania, and from the moderate to the low (60–90) class in the FL area of Po Plain. Under the P3 climate conditions, however, the MFI values in the FL area should increase up to the level of P1. Otherwise, no remarkable variation of MFI has been recorded, or is expected, in the CV and PL cropping system areas of Sicily and Sardinia, respectively.

3.1.3. Relationship between pedological and climatic variables

The correlations between the pedological and climatic variables obtained in each test area proved the most significant relationship between IDM vs. SOC (Table 3). The stability of the IDM vs. SOC relationship in the P1 and P2 time-periods was assessed for the test areas with adequate samples number in P1 (1961–1990). Figs. 3 and 4 show the regression equations related to CV and FL, for which SOC and IDM data were available for 18 and 24 profiles, respectively. The equations of P2 produced a better result than in P1, probably because of the number of replicates used in P2 and, in the case of CV, the less pronounced spatial variability of soil characteristics.

From the observation of Figs. 3 and 4, a clear climatic differentiation between the two test areas emerges. Nevertheless, the parallelism test confirms the temporal stability of the relation that binds the IDM index to the SOC content. The parallelism test shows that, in both areas, there is a significant relationship ($p < 0.001$), while there is no difference between the angular coefficients of the two pairs of regression lines (1981–2010 and 1961–1990).

The relationships between IDM and SOC in the OA and PL cropping systems that were found in P2 were used to estimate SOC in P3, according to the following equations:

$$SOC_P3_OA = 0.0634*IDM_P2 - 0.2035 \ (R^2 = 0.20, p < 0.05)$$

$$SOC_P3_PL = 0.0499*IDM_P2 + 0.0526 \ (R^2 = 0.28, p < 0.01).$$

3.1.4. Dynamics of carbon stock and soil physical quality indicators under different cropping systems

The SOC variations in the three time periods under study impact both carbon stock and soil physical quality indicators in a very different way, according to the considered cropping system. In the CV cropping system of Sicily, in particular, C_{stock} shows a marked increase of 12.6% passing from P1 to P2, but a reduction of more than 11% in P3, which leads back to values close to that of P1 (Table 7 and Fig. 5). In CV, SOC variations influence notably soil susceptibility to compaction and formation of surface crust, but not erodibility. Actually erodibility is more affected by clay than by SOC content (see Section 2.4.4) and Vertisols of CV are very rich in clay. Estimated soil losses in the three time-periods point to an increase from P1 to P2, followed by a relative decrease in P3, because of the marked reduction of precipitation (Table 6). However, erosion losses are always high and far beyond what is generally considered as tolerable erosion rate (about 1.4 Mg ha^{-1} yr^{-1}, Verheijen et al., 2009) and also the mean soil loss rate in European Union, estimated as 2.46 Mg ha^{-1} yr^{-1} (Panagos et al., 2015).

C_{stock} in the Luvisols under meadows of Sardinia (PL) results in

Table 6
Average (minimum and maximum) values of climatic variables, related to the three time-periods (P1: 1961–1990, P2: 1981–2010 and P3: 2021–2050) in the four cropping systems areas; CV: Cereals on clayey Vertisols; PL: Permanent pasture and meadows on sandy loam Luvisols; OA: Olive tree cultivation on loamy Andosols; FL: Forage and livestock production on loamy Luvisols.

	Cropping system	P (mm)		T (°C)		IDM*		MFI**		BGI***	
	CV	564.3	(473.1–665.7)	16.3	(13.9–18.0)	21.8 b	(17.8–30.0)	79.3 f	(90.7–70.2)	152.8 m	(178.9–115.4)
P 1 (1961–1990)	PL	522.8	(473.5–562.9)	16.6	(15.3–17.8)	20.4 b	(17.0–31.0)	71.2 f	(80.8–65.0)	153.2 m	(174.0–128.9)
	OA	996.8	(849.5–1107.4)	14.7	(13.0–16.0)	42.2 d	(35.7–51.7)	123.5 h	(138.5–98.3)	53.8 l	(78.6–36.9)
	FL	924.9	(749.5–1278.8)	12.4	(10.9–13.4)	41.4 d	(31.9–56.2)	104.6 g	(155.6–83.2)	22.0 k	(36.0–9.4)
	CV	606.8	(530.7–687.2)	16.7	(14.4–18.4)	23.1 b	(19.3–37.9)	84.9 f	(98.6–78.7)	147.0 m	(178.5–118.1)
P 2(1981–2010)	PL	502.8	(439.7–529.7)	16.8	(15.5–18.1)	19.4 a	(15.6–29.7)	70.3 f	(75.0–62.9)	155.5 m	(182.1–134.2)
	OA	847.1	(742.3–934.9)	14.6	(12.4–16.6)	35.6 c	(31.6–41.6)	102.3 g	(114.8–86.1)	67.6 l	(96.4–46.5)
	FL	830.0	(710.8–975.1)	13.1	(11.5–13.9)	36.0 c	(29.6–44.0)	96.9 g	(120.0–81.6)	24.0 k	(38.9–13.0)
	CV	532.7	(466.1–602.7)	17.5	(15.2–19.3)	19.7 a	(16.4–32.3)	71.3 f	(82.9–66.1)	165.1 m	(200.5–132.6)
P 3(2021–2050)	PL	540.0	(472.2–569.2)	17.7	(16.2–19.0)	20.2 b	(16.2–30.8)	74.3 f	(79.5–66.7)	160.9 m	(188.5–138.9)
	OA	877.1	(772.2–955.0)	16.3	(14.5–17.9)	33.7 c	(28.6–41.4)	93.1 g	(104.5–78.4)	44.3 k	(63.1–30.4)
	FL	947.7	(810.8–1159.3)	13.8	(12.2–14.7)	41.5 d	(32.0–56.3)	103.7 g	(128.4–87.3)	19.3 k	(31.2–10.4)

Mean annual precipitation (P), mean annual temperature (T) and De Martonne aridity index (IDM) are calculated from annual data, while aggressiveness index (MFI) and Bagnouls-Gaussen aridity Index (BGI) are calculated from monthly data.

* Different letters refer to different IDM aridity classes, as follow: a = semiarid; b = dry sub-humid; c = sub-humid; d = humid.

** Different letters refer to different MFI classes (CORINE, 1992), as follow: e = very low (< 60); f = low (60–90); g = moderate (90–120); h = high (120–160); i = very high (> 160).

*** Different letters refer to different BGI classes (CORINE, 1992), as follow: j = humid (0); k = moist (0–50); l = dry (50–130); m = very dry (> 130).

stable and no significant variations in soil susceptibility to compaction, formation of surface crust, and erodibility have been observed or are expected in the future. On the other hand, soil losses show slight changes in absolute, but much more evident in relative terms. In particular, there should be an increase of 13.5% in the future time frame, because of increased precipitation volume (7.4%) and aggressiveness (6.4% MFI) (Table 6). It must be pointed out that the erosion rate here is the lowest among the studied cropping systems, given the almost flat morphology of this test area. Nevertheless, also here the erosion rates exceed the threshold of tolerability.

In the Andosols of Campania under olive trees (OA) C_{stock} shows a progressive reduction, declining a 14% from P1 to P2 and a further 6.3% from P2 to P3. The variations are reflected in the worsening of soil susceptibility to compaction, formation of surface crust, and erodibility. Soil losses, which reduced of 18.3% from P1 to P2, show an increase in P3 of 4.6%. The more than proportional increase of soil erosion than rainfall in P3 (Table 6) is due to the interaction with the augmented soil erodibility.

Finally, the Po Plain soils of the FL cropping system show a decrease of C_{stock} in P2 compared to P1, but a substantial increase in P3 (28.8%). Soil physical quality indicators, which remained rather stable from P1 to P2, show in P3 a certain improvement, relatively more marked in the susceptibility to crusting. The values of the K soil erodibility index in FL are always the highest, on average 0.041, which is comparable to most erodible soils of Europe (Panagos et al., 2014). As a consequence, soil losses are always high (on average 28.0 Mg ha^{-1} y^{-1}) in spite of the gentle slopes, and the estimated erosion rate, which decreased from P1 to P2 about 19%, is expected to increase 8.6% in P3.

4. Discussion

According to the SCIA network (http://www.scia.isprambiente.it/home_new.asp), temperature variations for the whole of Italy occurred especially in the period from 1961 to 2010. In the decade 1981–1990,

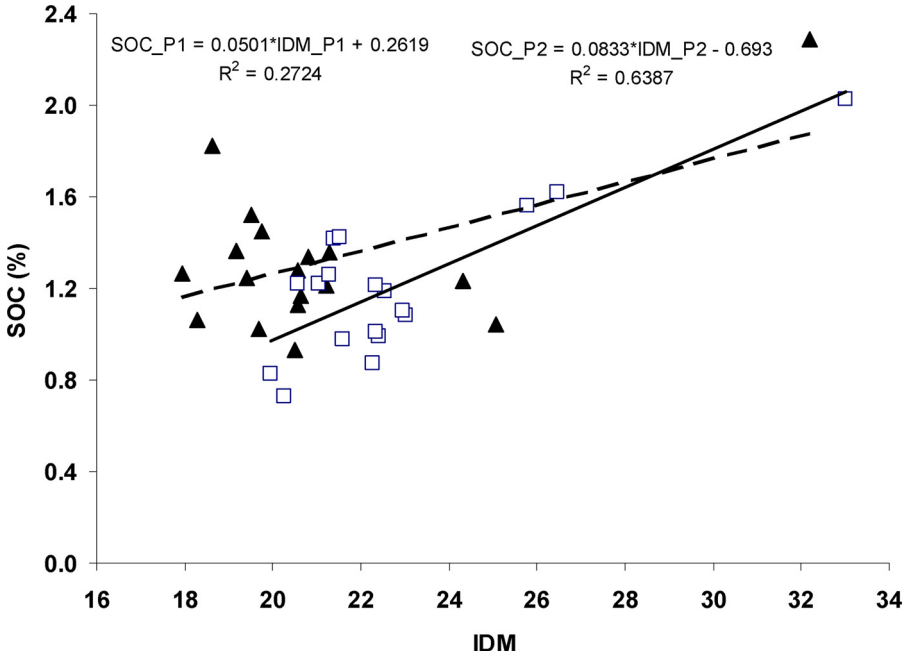

Fig. 3. Regressions between the soil organic carbon (SOC) content and the de Martonne index (IDM) values of the period 1 (P1: 1961–1990) and period 2 (P2: 1981–2010) related to the 18 profiles sampled in the cereal cropping system (CV) on Vertisols of Sicily. White squares refer to P1 time period; black triangles refer to P2 time period.

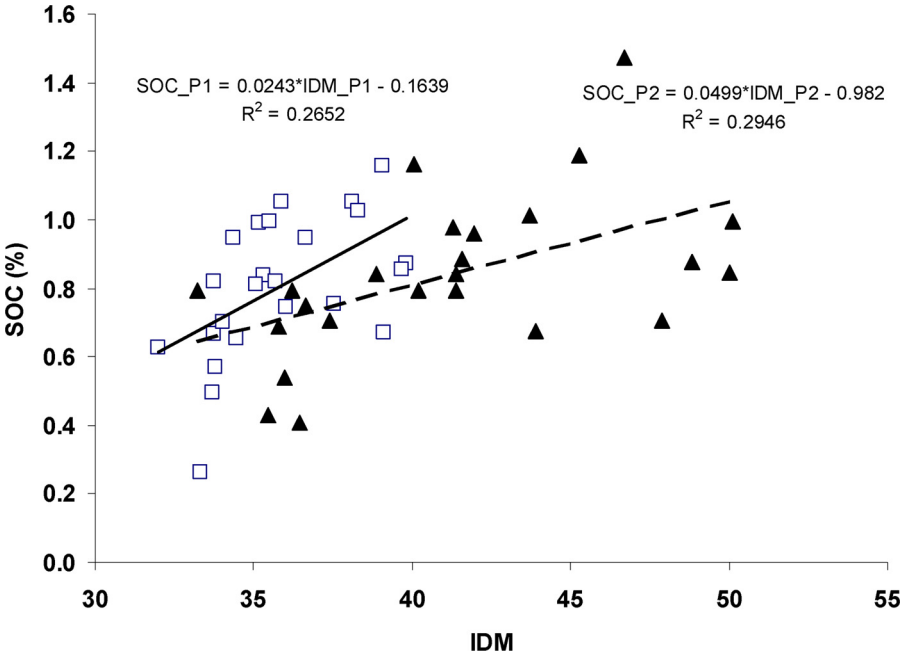

Fig. 4. Regressions between the soil organic carbon (SOC) content and the de Martonne index (IDM) values of the period 1 (P1: 1961–1990) and period 2 (P2: 1981–2010) related to the 24 profiles sampled in the forage and livestock production (FL) cropping system on the loamy Luvisols of Po Plain. White squares refer to P1 time period; black triangles refer to P2 time period.

in particular, a marked breakpoint occurred with an increase of 0.9 °C in 1987. Therefore, we believe that the variations observed in the study areas in two thirty-year periods (1961–90 and 1981–2010) give an effective representation of the climatic differences between past and current conditions. The effect of climate change on the precipitation trend instead was more variable and showed a significant inter-annual variability, as also reported by other authors (Dunkeloh and Jacobeit, 2003; MedCLIVAR, 2007; Mariani and Parisi, 2014).

The variations of the aridity index IDM can be compared to those obtained by other authors who studied desertification trends in Italy. In a study aimed at assessing sensitivity to land degradation over Italy during a long-term period (1960–2008), Salvati and Bajocco (2011) observed the same generalized decrease with respect to mean annual rainfall and FAO-UNEP aridity index, for which, similarly to IDM, lower scores indicate more arid conditions.

It is worthy to be noted that in FL and PL, P1 and P3 climatic indexes are rather similar and both different from P2. This would mean that the major change actually occurred between P1 and P2, while the estimated climatic conditions of P3 are rather similar to P1. In the FL area, in particular, IDM is expected to increase by more than 5 units, with a consequent return to the humid class. In CV instead, IDM values point to a future aridification and in the OA cropping system IDM progressively diminishes in the three time periods, shifting from humid in P1 to sub-humid in P2 and P3.

The values of carbon stock resulting from this study are lower than those reported for all European cropland soils, on average 4.57 kg m^{-2} in P1, 4.50 in P2, and 4.45 in P3, versus 5.30 kg m^{-2} of P1 years (Smith et al., 2001); however, it is worthy to note how they vary significantly between cropping system and soil. The effect of the considered type of soil, in particular, is evidenced by a comparison with the average values reported in Chiti et al. (2011) for the same depth and cropping systems, in the same time frame of P2, and analogues climatic and morphological conditions, but without soil differentiation. The particular ability of Andosols to store carbon is highlighted in the C_{stock} of OA, which is on average 5.68 kg m^{-2}, while it is 5.07 kg m^{-2} in the mentioned work, but it is 4.0 kg m^{-2} in Spain, on others soil typologies than Andosols (Rodríguez-Murillo, 2001). Similarly, the capacity of Vertisols to sequester carbon is shown by the comparison of average CV value in P2, that is 5.96 kg m^{-2}, versus the 4.62 kg m^{-2} reported by Chiti et al. (2011) and 5.08 kg m^{-2} reported in Spain for similar dryland farming and land use type (Rodríguez-Murillo, 2001).

The C_{stock} of loamy Luvisols of the forage cropping system in the Po Plain, instead, results in much lower, on average 2.88 kg m^{-2}, in comparison to the 5.12 kg m^{-2} under arable lands in same climatic and

Table 7
Descriptive statistics (mean values and standard error) of the soil physical quality indicators related to SOC content, and estimated erosion rate according to the RUSLE model, for the compared periods and cropping systems. CV: Cereals on clayey Vertisols; PL: Permanent pasture and meadows on sandy loam Luvisols; OA: Olive tree cultivation on loamy Andosols; FL: Forage and livestock production on loamy Luvisols.

Period	Cropping system	C stock (kg m^{-2})		K (soil erodibility)		Compaction susceptibility (dimensionless)		Crusting susceptibility (dimensionless)		Erosion rate by RUSLE model (Mg ha^{-1} y^{-1})	
P1 (1961–1990)	CV	5.21	2.77E-03	0.0284	7.80E-07	1.783	1.34E-04	0.922	1.01E-04	30.3	2.13E-01
	PL	3.49	3.27E-03	0.0379	4.10E-06	1.805	1.82E-04	1.683	4.37E-04	4.0	8.85E-02
	OA	6.52	2.08E-02	0.0345	3.95E-05	1.656	7.39E-04	1.256	1.65E-03	20.7	6.16E-01
	FL	3.07	4.14E-03	0.0413	3.62E-06	1.879	2.59E-04	2.014	6.21E-04	30.5	3.97E-01
P2 (1981–2010)	CV	5.96	3.36E-03	0.0283	7.89E-07	1.744	1.43E-04	0.894	1.09E-04	33.7	2.33E-01
	PL	3.49	3.27E-03	0.0379	4.31E-06	1.804	1.94E-04	1.681	4.61E-04	3.7	8.25E-02
	OA	5.68	1.13E-02	0.0362	2.18E-05	1.697	5.63E-04	1.343	1.23E-03	17.5	5.21E-01
	FL	2.88	4.27E-03	0.0413	3.65E-06	1.884	2.72E-04	2.025	6.60E-04	25.6	3.25E-01
P3	CV	5.29	3.02E-03	0.0285	6.04E-07	1.774	1.34E-04	0.916	1.01E-04	31.8	2.21E-01
(2021–2050)	PL	3.48	3.40E-03	0.0378	4.58E-06	1.797	1.94E-04	1.665	4.73E-04	4.2	9.10E-02
	OA	5.32	1.51E-02	0.0367	2.72E-05	1.711	7.74E-04	1.370	1.55E-03	18.3	5.46E-01
	FL	3.71	8.41E-03	0.0405	8.94E-06	1.835	4.79E-04	1.909	1.15E-03	27.8	3.55E-01s

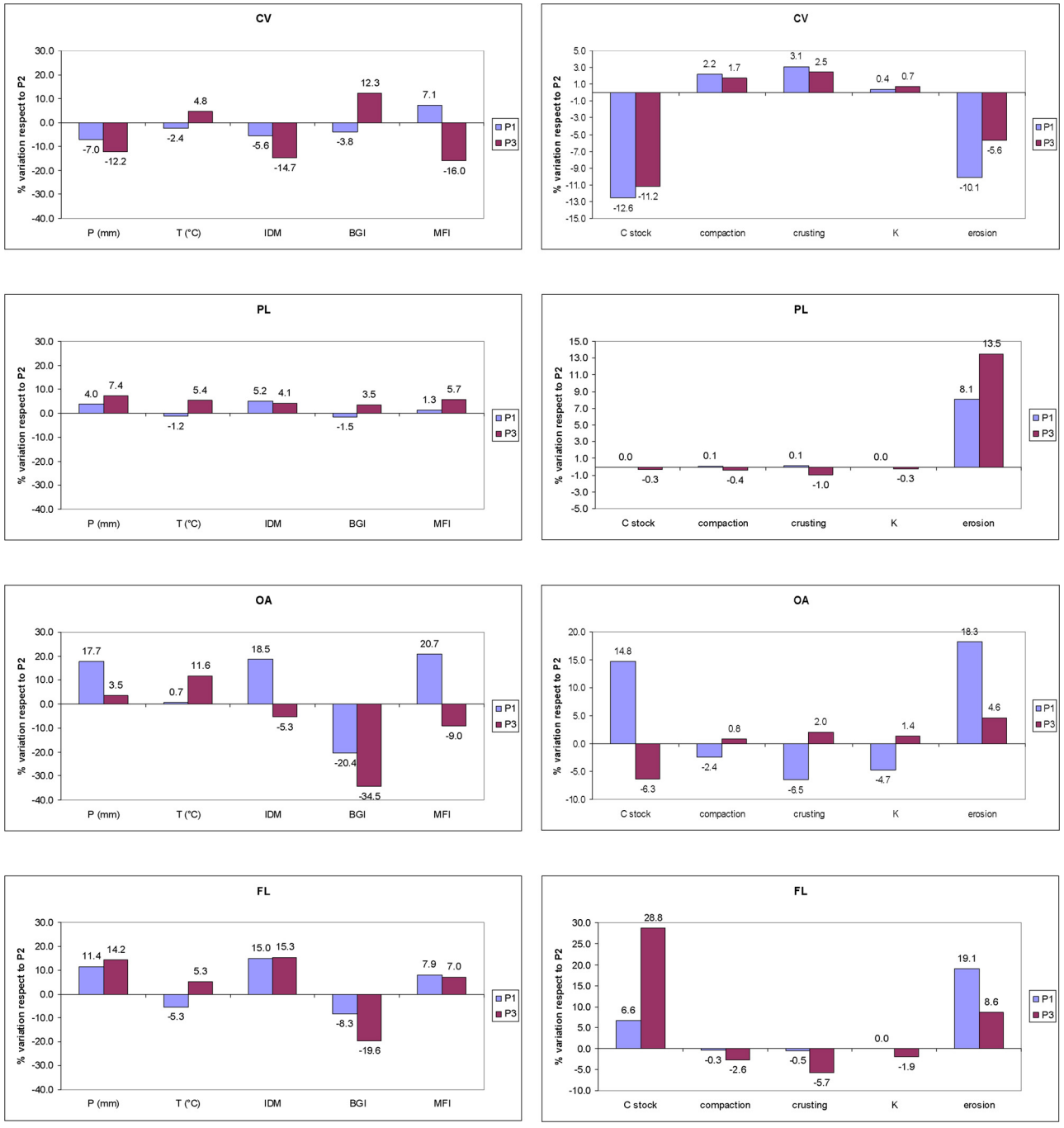

Fig. 5. Percentage of variation of the variables in the period 1 (P1) and period 3 (P3) in comparison with their values under the period 2 (P2, used as control) in the studied cropping systems (CV: Cereals on clayey Vertisols; PL: Permanent pasture and meadows on sandy loam Luvisols; OA: Olive tree cultivation on loamy Andosols; FL: Forage and livestock production on loamy Luvisols). The figures on the left are related to climate variables, the figures on the right refer to soil physical quality indicators.

morphological conditions of Chiti et al. (2011) and to the average of 5.76 kg m^{-2} reported in Spain for analogous irrigated farming (Rodríguez-Murillo, 2001). A comparison of the C_{stock} of sandy loam Luvisols under pastures of Sardinia can be only made with the equivalent value referred to all soils and climates of Spain, which is however much higher, i.e., 7.32 kg m^{-2} (Rodríguez-Murillo, 2001).

The interaction between carbon stock and climate change is significantly different in the considered cropping systems. Cereals on Vertisols are the most negatively affected by the aridification of climate, followed by olive tree cultivation on Andosols. The forage cropping system on Luvisols instead is deemed to recover its ability to store carbon, while C_{stock} in permanent pastures on Luvisols remains nearly the same throughout the years.

Soil erodibility (K) and susceptibility to compaction and crusting are the soil quality indicators that, on the whole, show minor variations, both in absolute and relative terms, during the three considered time periods (Table 7 and Fig. 5). However, it must be considered that even minor K variations can have an effect on the final erosion rate from a given storm, as it can vary by a rate of up to 6 times (from 0.010 to 0.060, Murphy, 2014).

If the dynamics of soil erodibility and susceptibility to compaction and crusting are inversely related with C_{stock}, there are no univocal

relationships between C_{stock} and erosion rate (Fig. 5). In fact, water erosion potential is only partially affected by C_{stock} and soil erodibility, while the rainfall erosivity of the area, the length and degree of slope of the field, and the land management factors regulating surface runoff, can play a major role (Rosewell and Loch, 2002). In a study carried out in a semiarid Mediterranean ecosystem in Spain, García-Fayos and Bochet (2009) found strong correlations between climate change, soil erosion, negative impacts on SOC content, and related soil physical properties, namely aggregate stability, bulk density, and water-holding capacity. Therefore, it can be assumed that if climate change increases soil erosion, it will also damage soil properties. In the case of FL, in particular, the expected increase in rainfall quantity is the reason of the forecasted raise of soil erosion, which counteracts the positive effect exerted by the SOC increase. In CV instead, the foreseen lower precipitation and consequent aridification causes a marked C_{stock} decrease, but only a soil loss reduction of about 5% is expected.

5. Conclusions

Our research findings confirm that climosequences are useful to estimate the future dynamics of some soil edaphic properties resulting from climate change. This methodology, based on the "space for climate substitution" approach, makes it possible to evaluate the effect of probable future climatic conditions on some soil properties and physical quality indicators, once significant relationships have been identified between SOC and specific climatic indexes. In our study, the De Martonne aridity index resulted in the best correlation with SOC content, in all the studied cropping systems. The relationships were not significantly different in the past and in the present time, and are expected to remain valid in the future.

In the four geographical regions, the climate-soil-cropping system interaction was different; Sicily, with cereal crops on clayey Vertisols, and Po Plain, with forage and livestock production on loamy Luvisols, were the areas and cropping systems most sensitive to future climate condition, followed by olive tree cultivation on loamy Andosols, while permanent pasture and meadows on Luvisols were the most resilient. It is worthy to highlight that current large differences in climate and soil physical quality indicators between northern and southern Italy are expected to increase in the future, resulting in a more marked soil differentiation between the temperate and subtropical agricultural areas of the country.

Soil C_{stock} and soil loss by water erosion were the indicators most sensitive to climate change, while compaction and crusting susceptibility, and erodibility, resulted little affected by climate change, even when soil organic carbon variations were prominent. As a whole, the three considered physical qualities resulted proportionally less affected than climatic variables by temporal changes. This outcome confirms the fundamental role of soil physics in controlling the resilience of the soil system to climate change. Soil physical qualities also resulted proportionally more affected by the cropping system than by climate, as already found by other authors (Reeves, 1997; Guo and Gifford, 2002; Lal, 2004).

Future research issues may consider the sensitivity of soil indicators based on chemical properties and qualities to climate. With a similar approach, based on cropping systems on specific soil types along climosequences, variations of important components of soil fertility, such as cation exchange capacity, base saturation, pH, nutrient availability, salinity, and alkalinity, could be investigated. Finally, the usefulness of the described methodology might also be tested to estimate soil biology behaviour and gas emissions driven by current and future climate changes.

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